REPORT DOCUMENTATION PAGE

FORM APPROVED
OMB NO. 0704-0188

1. AGENCY USE ONLY (leave blank)	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	September 2000	Final Report

4. TITLE AND SUBTITLE OF REPORT
Native-Oxide-Defined Semiconductor Quantum Well Lasers and Optoelectronic Devices: Al-Based III-V Native Oxides

5. FUNDING NUMBERS
DAAH04-96-1-0333

6. AUTHOR(S)

N. Holonyak Jr.

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

University of Illinois
Department of Electrical and Computer Engineering
155 Everitt Laboratory
1406 W. Green St.
Urbana, IL 61801-2991

8. PERFORMING ORGANIZATION REPORT NUMBER:

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

US Army Research Office
PO Box 12211
Research Triangle Park, NC 27709-2211

10. SPONSORING/MONITORING AGENCY REPORT NUMBER:
ARO 35783.13-EL

11. SUPPLEMENTARY NOTES:

The views, opinions, and/or findings contained in this report are those of the author(s) and should not be considered as the official Department of Army position, policy, or decision, unless so designated by other documentation.

12a. DISTRIBUTION AVAILABILITY STATEMENT

Approved for public release; distribution unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT (Maximum 200 words)

The study and use of Al-based III-V native oxide in quantum well heterostructure (QWH) devices has been pioneered in this project, and since the time of its introduction (1990) has grown into an international activity. An almost all-oxide enclosed microcavity laser and LED have been realized in the latter stages of this project. By employing a tunnel junction contact as a mechanism to invert lateral (edgewise) electron current into injection hole current (and thus accomplish laterally offset carrier injection), we have demonstrated oxide-confined edge emitter and vertical cavity surface emitting lasers (VCSELs) driven entirely with lateral electron currents, and thus with reduced resistive losses in spite of the offset current source. This is potentially important for optoelectronic IC development. The use of the Al-based III-IV native oxide to thwart hydrolyzation and increase device reliability has been demonstrated.

14. SUBJECT TERMS

Al-based native oxide, III-V native oxide, "wet" oxidation, buried III-V oxide, oxide-defined lasers, lateral oxidation, oxide-defined disk lasers, oxide-defined ring lasers, coupled ring lasers, coupled-disk photonic ~~lattice~~, quantum-well photonic lattice, oxide post photonic lattice, oxide-defined high-Q cavity.

15. NUMBER OF PAGES: 16

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	UL

STANDARD FORM 298 (REV 2-88)

NATIVE-OXIDE-DEFINED SEMICONDUCTOR QUANTUM WELL LASERS AND OPTOELECTRONIC DEVICES: Al-BASED III-V NATIVE OXIDES

N. Holonyak, Jr.

FINAL
REPORT

September 2000

PREPARED FOR
U.S. ARMY RESEARCH OFFICE

DAAH04-96-1-0333
1-5-20682

Department of Electrical and Computer Engineering
University of Illinois at Urbana-Champaign
Urbana, IL 61801

TABLE OF CONTENTS

ABSTRACT.. 3

I. INTRODUCTION... 4

II. AL-BASED III-V OXIDE TECHNOLOGY 5

III. AL-BASED III-V NATIVE OXIDE PROPERTIES AND DEVICES........................ 5

IV. CONCLUSIONS.. 6

REFERENCES.. 8

ABSTRACT

The study and use of the Al-based III-V native oxide in quantum well heterostructure (QWH) devices has been pioneered in this project, and since the time of its introduction (1990) has grown into an international activity. An almost all-oxide enclosed microcavity laser and LED have been realized in the latter stages of this project. By employing a tunnel junction contact as a mechanism to invert lateral (edgewise) electron current into injection hole current (and thus accomplish laterally offset carrier injection), we have demonstrated oxide-confined edge emitter and vertical cavity surface emitting lasers (VCSELs) driven entirely with lateral electron currents, and thus with reduced resistive losses in spite of the offset current source. This is potentially important for optoelectronic IC development. The use of the Al-based III-V native oxide to thwart hydrolyzation and increase device reliability has been demonstrated.

I. INTRODUCTION

Over the years this project has been the source of many developments in quantum well (QW) lasers, including (besides the coining of the "QW" name): (1) the first construction of a p-n diode QW laser (1977); (2) the first continuous room temperature operation of a QW laser (1978); (3) the discovery of impurity-induced layer disordering (IILD) of QW heterostructures and the use of IILD in defining the geometry of QW lasers and waveguides (1980), which was patented and now is widely used in industry; (4) the discovery of the Al-based III-V native oxide and its use in defining QW lasers and waveguides (1990), which also was patented and is now coming into wide use in industry; and (5) the introduction of offset tunnel junction contacts to minimize the hole conduction path (distance) in low-mobility p-type crystal and thereby make possible high-mobility lateral electron current biasing of fully oxide enclosed (compact) vertical cavity surface emitting lasers (VCSELs). Note that the buried oxide aperture that now is so important in VCSELs comes from this project, first being demonstrated on edge emitters. The last two developments listed above (the Al-based III-V native oxide and the offset tunnel junction contact) have generated 13 issued patents. The last patent concerns the offset tunnel contact that makes possible all-electron-current lateral biasing of lasers . These patents are listed at the end of this report, as well as a representative list of some of the papers leading to the patents.

II. Al-BASED III-V OXIDE TECHNOLOGY

The basic Al-based III-V native-oxide technology generated in this project is described by the patents of Refs. 1, 4, 8, 9, 10, and 12, and by the papers of Refs. 14, 17, 22, 24, and 27 (and to some further extent in all the other patents and papers listed).

III. Al-BASED III-V NATIVE OXIDE PROPERTIES AND DEVICES

The first devices demonstrated via the use of the Al-based III-V native oxide were various forms of stripe QW lasers (see Refs. 15, 16, and 18). These have included the generalization from the use of the prototype oxidizable ternary $Al_xGa_{1-x}As$ to the higher gap visible-spectrum quaternary $In_{0.5}(Al_xGa_{1-x})_{0.5}P$ (Refs. 19, 20, 21, 22, and 28). In other words, we established very early in this work the importance of the oxidizable component Al in the III-V to be oxidized. We also showed very early that the III-V oxidation procedure could be important in improving crystal and device reliability (Refs. 17, 28, and 33).

From the very beginning (1990, Ref. 14) we established that the formation of the Al-based III-V native oxide is highly sensitive to the Al concentration and hence has the special capability of being formable as a buried oxide. A buried III-V layer with a sufficient Al concentration can be oxidized edgewise, and thus can be buried sandwiched between lower Al composition layers. The buried oxide is unique and makes possible unique applications, one being a simple form of higher reliability so-called window laser, e.g., as described in Refs. 21 and 25. In fact, in certain circumstances native oxide current-blocking windows can be formed on a finished (already processed) QW laser

(Ref. 25), just as for certain light emitting devices the reliability can be enhanced by, surprisingly, oxidation of the finished device (Refs. 8 and 28).

One of the more important uses of the buried oxide introduced in this project, and now used world-wide, is the oxide aperture used to define the current and the electromagnetic field in a QW laser. We demonstrated this use of the buried oxide on edge-emitter QW lasers (Ref. 23), and a year later it was picked up by VCSEL researchers. It owes its existence to the work of this project and now has become the preferred way of constructing VCSELs.

Because the Al-based III-V native oxide is very sensitive in its formation to the Al composition, and thus has the important property that it can be formed edgewise as a buried oxide, in fact, even as a stack of buried oxide layers, the oxide can be employed as one of the component layers of distributed Bragg reflectors (DBR) of VCSELs, either photopumped (Ref. 26) or current-driven devices (Refs. 30 and 31). It is worth mentioning that it is the buried form of the oxide that represents the only case of the Al-based III-V oxide that has been adequate to demonstrate field effect transistor operation (Ref. 27). Thus far, however, the Al-based III-V native oxide has been most successful in defining the geometry of optoelectronic devices, for example, lasers, waveguides, and LEDs, and has been less successful in field effect device applications.

IV. CONCLUSIONS

In the 10 years since the pioneering introduction of the Al-based III-V native oxide in optoelectronics in this project, not only have we been responsible for 13 patents (a half-dozen fundamental and controlling quite broadly the use of the oxide) and 60 or

more journal articles, a dozen Ph.D. students have finished their research in this area of work and are employed in optoelectronics R & D (oxide included) in industry. The journal literature indicates many more individuals and laboratories are working on the further study and exploitation of the Urbana Al-based III-V native oxide, which is rapidly becoming an important III-V semiconductor optoelectronics technology (including for IC purposes).

REFERENCES

A. PATENTS

1. Nick Holonyak, Jr. and John M. Dallesasse, U.S. Patent #5,262,360, November 16 1993, "AlGaAs NATIVE OXIDE" (Filed June 24 1991, continuation in part of December 31 1990 filing).

2. Nick Holonyak, Jr., F. A. Kish, and S. J. Caracci, U.S. Patent #5,327,448, July 5 1994, "SEMICONDUCTOR DEVICES AND TECHNIQUES FOR CONTROLLED OPTICAL CONFINEMENT" (Filed March 30 1992).

3. Nick Holonyak, Jr., N. El-Zein, and F. A. Kish, U.S. Patent #5,353,295, October 4 1994, "SEMICONDUCTOR LASER DEVICE WITH COUPLED CAVITIES" (Filed August 10 1992).

4. Nick Holonyak, Jr. and John M. Dallesasse, U.S. Patent #5,373,522, December 13 1994, "SEMICONDUCTOR DEVICES WITH NATIVE ALUMINUM OXIDE REGIONS" (Filed September 7 1993; continuation in part of Ser. No. 636,313, December 31 1990, abandoned).

5. M. J. Ludowise, N. Holonyak, Jr., S. J. Caracci, M. R. Krames, and F. A. Kish, U.S. Patent #5,400,354, March 21 1995, "LAMINATED UPPER CLADDING STRUCTURE FOR A LIGHT EMITTING DEVICE" (Filed February 9 1994; Serial #08-193,681).

6. Nick Holonyak, Jr., F. A. Kish, and S. J. Caracci, U.S. Patent #5,403,775, April 4 1995, "METHOD OF MAKING SEMICONDUCTOR DEVICES AND TECHNIQUES FOR CONTROLLED OPTICAL CONFINEMENT" (Filed June 15 1994).

7. N. Holonyak, Jr., N. El-Zein, F. A. Kish, U. S. Patent #5,425,043, June 13 1995, "SEMICONDUCTOR LASER" (Filed August 9 1994; Division of Ser. No. 927 822, August 10 1992, Patent # 5,353,295).

8. N. Holonyak, Jr., T. A. Richard, M. R. Keever, F. A. Kish, C. Lei, and S. L. Rudaz, U.S. Patent #5,517,039, May 14 1996, "SEMICONDUCTOR DEVICES FABRICATED WITH PASSIVATED HIGH ALUMINUM-CONTENT III-V MATERIAL" (Filed November 14 1994).

9. Nick Holonyak, Jr., S. A. Maranowski, and F. A. Kish, U.S. Patent #5,550,081, August 27 1996, "METHOD OF FABRICATING A SEMICONDUCTOR DEVICE BY OXIDIZING ALUMINUM-BEARING III-V SEMICONDUCTOR IN WATER VAPOR ENVIRONMENT" (Filed March 31 1995; continuation of Ser. No. 224,838, April 8 1994).

10. Nick Holonyak, Jr. and J. M. Dallesasse, U.S. Patent #5,567,980, October 22 1996, "NATIVE OXIDE OF AN ALUMINUM-BEARING GROUP III-V SEMICONDUCTOR" (Filed January 26 1995; continuation of 1990, 1991, and 1993 filings).

11. Nick Holonyak, Jr., S. A. Maranowski, and F. A. Kish, U.S. Patent #5,581,571, December 3 1996. "SEMICONDUCTOR DEVICES AND METHODS" (Filed June 7 1995; division of Ser. No. 414,432, March 31 1995, which is continuation of Ser. No. 224,838, April 8 1994).

12. Nick Holonyak, Jr. and J. M. Dallesasse, U. S. Patent #5,696,023, December 9, 1997, "METHOD FOR MAKING ALUMINUM GALLIUM ARSENIDE SEMICONDUCTOR DEVICE WITH NATIVE OXIDE LAYER" (FILED June 7, 1995; continuation of 1990, 1991 and 1993 filings).

13. Nick Holonyak, Jr. J. J. Wierer, and P. W. Evans, U.S. Patent #5,936,266, August 10, 1999, "SEMICONDUCTOR DEVICES AND METHODS WITH TUNNEL CONTACT HOLE SOURCES" (Filed Oct, 1997).

B. PAPERS

14. J. M. Dallesasse, N. Holonyak, Jr., A. R. Sugg, T. A. Richard, and N. El-Zein, "Hydrolyzation Oxidation of $Al_xGa_{1-x}As$-AlAs-GaAs Quantum Well Heterostructures and Superlattices," Appl. Phys. Lett. 57, 2844-2846 (24 December 1990).

15. J. M. Dallesasse and N. Holonyak, Jr., "Native-Oxide Stripe-Geometry $Al_xGa_{1-x}As$-GaAs Quantum Well Heterostructure Lasers," Appl. Phys. Lett. 58, 394-396 (28 January 1991).

16. J. M. Dallesasse, N. Holonyak, Jr., D. C. Hall, N. El-Zein, A. R. Sugg, S. C. Smith, and R. D. Burnham, "Native-Oxide-Defined Coupled-Stripe $Al_xGa_{1-x}As$-GaAs Quantum Well Heterostructure Lasers," Appl. Phys. Lett. 58, 834-836 (25 February 1991).

17. A. R. Sugg, N. Holonyak, Jr., J. E. Baker, F. A. Kish, and J. M. Dallesasse, "Native Oxide Stabilization of AlAs-GaAs Heterostructures," Appl. Phys. Lett. 58, 1199-1201 (18 March 1991).

18. T. A. Richard, F. A. Kish, N. Holonyak, Jr., J. M. Dallesasse, K. C. Hsieh, M. J. Ries, P. Gavrilovic, K. Meehan, and J. E. Williams, "Native-Oxide Coupled-Stripe $Al_yGa_{1-y}As$-GaAs-$In_xGa_{1-x}As$ Quantum Well Heterostructure Lasers," Appl. Phys. Lett. 58, 2390-2392 (27 May 1991).

19. F. A. Kish, S. J. Caracci, N. Holonyak, Jr., J. M. Dallesasse, A. R. Sugg, R. M. Fletcher, C. P. Kuo, T. D. Osentowski, and M. G. Craford, "Native-Oxide Stripe-Geometry $In_{0.5}(Al_xGa_{1-x})_{0.5}P$-$In_{0.5}Ga_{0.5}P$ Heterostructure Laser Diodes," Appl. Phys. Lett. 59, 354-356 (15 July 1991).

20. F. A. Kish, S. J. Caracci, N. Holonyak, Jr., S. A. Maranowski, J. M. Dallesasse, R. D. Burnham, and S. C. Smith, "Visible Spectrum Native-Oxide Coupled-Stripe $In_{0.5}(Al_xGa_{1-x})_{0.5}P$-$In_{0.5}Ga_{0.5}P$ Quantum Well Heterostructure Laser Arrays," Appl. Phys. Lett. 59, 2883-2885 (25 November 1991).

21. S. A. Maranowski, F. A. Kish, S. J. Caracci, N. Holonyak, Jr., J. M. Dallesasse, D. P. Bour, and D. W. Treat, "Native-Oxide Defined $In_{0.5}(Al_xGa_{1-x})_{0.5}P$ Quantum Well Heterostructure Window Lasers (660 nm)," Appl. Phys. Lett. 61, 1688-1690 (5 October 1992).

22. F. A. Kish, S. J. Caracci, N. Holonyak, Jr., K. C. Hsieh, J. E. Baker, S. A. Maranowski, A. R. Sugg, J. M. Dallesasse, R. M. Fletcher, C. P. Kuo, T. D. Osentowski, and M. G. Craford, "Properties and use of $In_{0.5}(Al_xGa_{1-x})_{0.5}P$ and $Al_xGa_{1-x}As$ Native Oxides in Heterostructure Lasers," J. Electron. Mater. 21, 1133-1139 (December 1992).

23. S. A. Maranowski, A. R. Sugg, E. I. Chen, and N. Holonyak, Jr., "Native Oxide Top- and Bottom-Confined Narrow Stripe p-n $Al_yGa_{1-y}As$-GaAs-$In_xGa_{1-x}As$ Quantum Well Heterostructure Laser," Appl. Phys. Lett. 63, 1660-1662 (20 September 1993).

24. S. J. Caracci, M. R. Krames, N. Holonyak, Jr., M. J. Ludowise, and A. Fischer-Colbrie, "Long Wavelength (λ~1.5 μm) Native-Oxide-Defined InAlAs-InP-InGaAsP Quantum Well Heterostructure Laser Diodes," J. Appl. Phys. 75, 2706-2708 (1 March 1994).

25. S. A. Maranowski, E. I. Chen, N. Holonyak, Jr., and T. A. Richard, "$Al_xGa_{1-x}As$-GaAs-$In_yGa_{1-y}As$ Quantum Well Heterostructure Lasers with Native Oxide Current-Blocking Windows Formed on Metallized Devices," Appl. Phys. Lett. 64, 2151-2153 (18 April 1994).

26. M. J. Ries, T. A. Richard, S. A. Maranowski, N. Holonyak, Jr., and E. I. Chen, "Photopumped Room-Temperature Edge- and Vertical-Cavity Operation of AlGaAs-GaAs-InGaAs Quantum-Well Heterostructure Lasers Utilizing Native Oxide Mirrors," Appl. Phys. Lett. 65, 740-742 (8 Aug 1994).

27. E. I. Chen, N. Holonyak, Jr., and S. A. Maranowski, "$Al_xGa_{1-x}As$-GaAs Metal-Oxide Semiconductor Field Effect Transistors Formed by Lateral Water Vapor Oxidation of AlAs," Appl. Phys. Lett. 66, 2688-2690 (15 May 1995).

28. T. A. Richard, N. Holonyak, Jr., F. A. Kish, M. R. Keever, and C. Lei, "Postfabrication Native-Oxide Improvement of the Reliability of Visible-Spectrum AlGaAs-In(AlGa)P p-n Heterostructure Diodes," Appl. Phys. Lett. 66, 2972-2974 (29 May 1995).

29. J. J. Wierer, P. W. Evans, and H. Holonyak, Jr., "Buried Tunnel Contact Junction AlGaAs-GaAs-InGaAs Quantum Well Heterostructures Lasers With Oxide-Defined Lateral Currents," Appl. Phys. Lett. 71, 2286-2288 (20 Oct 1997).

30. J. J. Wierer, P. W. Evans, N. Holonyak, Jr., and D. A. Kellogg, "Lateral Electron Current Operation of Vertical Cavity Surface Emitting Lasers With Buried Tunnel Contact Hole Sources," Appl. Phys. Lett. 71, 3468-3470 (15 Dec 1997).

31. J. J. Wierer, D. A. Kellogg, and N. Holonyak, Jr., "Tunnel Contact Junction Native Oxide Aperture and Mirror Vertical Cavity Surface Emitting Lasers and Resonant Cavity Light Emitting Diodes," Appl. Phys. Lett. 74, 926-928 (15 Feb 1999).

32. N. Holonyak, Jr., "Is the Light Emitting Diode (LED) an Ultimate Lamp?," Am. J. Phys. 68, 864-866 (Sept, 2000).

33. D. A. Kellogg, N. Holonyak, Jr., and R. D. Dupuis, "Reliability of Photopumped $Al_xGa_{1-x}As$-GaAs Quantum Well Heterostructure Lasers With Top and Bottom Distributed Native-Oxide Reflectors," Appl. Phys. Lett. 77, 1608-1610 (Sept 11, 2000).